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DYNAMIC ROPS TEST FOR TRACTORS OVER 6,000 KILOGRAMS

Caleb M. Lindhorst
University of Nebraska-Lincoln, clindhorst2@gmail.com

Roger M. Hoy
University of Nebraska - Lincoln, rhoy2@unl.edu

Santosh Pitla
University of Nebraska-Lincoln, spitla2@unl.edu

Michael F. Kocher
University of Nebraska-Lincoln, mkocher1@unl.edu

TECHNICAL NOTE:

DYNAMIC ROPS TEST FOR TRACTORS OVER 6,000 KILOGRAMS

C. M. Lindhorst, R. M. Hoy, S. K. Pitla, M. F. Kocher

ABSTRACT. *OECD static tests (Codes 4, 6, 7, and 8) for agricultural rollover protective structures (ROPS) have become accepted standards for evaluating the ability of these structures to protect the operator during tractor rollover events. The strength properties of some materials typically used in ROPS change because of cold weather embrittlement at low temperatures. The static ROPS tests lack the ability to evaluate the strength of these structures during cold weather. The use of the dynamic ROPS test is well noted as a means for proving cold weather embrittlement resistance properties. Unfortunately, application of the OECD dynamic ROPS test (Code 3) is restricted to tractors with unballasted mass greater than 600 kg and generally less than 6,000 kg. The analyses presented in this technical note were undertaken to evaluate the extension of the OECD Code 3 dynamic ROPS test to tractors with unballasted mass of 6,000 kg or more. Tractor unballasted mass and wheelbase data from 47 wheeled tractors tested at the Nebraska Tractor Test Lab from 2014 to 2016 were used to explore the possibility of using a dynamic test method for evaluating the ability of ROPS on tractors with unballasted mass greater than 6,000 kg to meet the safety requirements of agricultural tractor ROPS. The data were graphed and analyzed to determine the required pendulum drop height and energy values to be applied to the ROPS by extending the existing equations to tractors over 6,000 kg. For tractors over 6,000 kg mass, it was determined that pendulum drop heights were too great for practical use. Three pendulum masses were proposed for the dynamic ROPS test: a 2,000 kg pendulum for tractors with mass less than 7,000 kg, a 4,000 kg pendulum for tractors with mass of 7,000 kg or more and less than 14,000 kg, and a 6,000 kg pendulum for tractors with mass of 14,000 kg or more and less than 23,000 kg. Alternate equations were developed for the drop height of each pendulum to meet the energy requirements that are expected to provide similar permanent deflections as those obtained when using the static ROPS test when considering the effect of strain rates on material properties. Tests should be conducted to determine how the results (permanent deflections) from the proposed dynamic ROPS test compare with results from the accepted static ROPS tests. It is further proposed that dynamic testing be conducted with the tractor rigidly restrained in a manner similar to the static test to better account for the wide variety of available tires and mountings for each tractor model.*

Keywords. *Energy, Impact test, Pendulum, Reference mass, ROPS, Tractors.*

Rollover protective structures (ROPS) are employed to limit the risks to operators resulting from rollover of tractors during normal use. ROPS were developed separately in North America and Europe starting in the 1950s and followed a progression from field overturn tests to dynamic or impact testing to the presently used static test method. In 1939, a farm study was done in the U.S. and determined that farm tractors had a higher frequency of being overturned than previously recognized (Arndt, 1971). Arndt (1971) also referred to a safety study conducted by the Farm Equipment Institute (FEI), which concluded that the issue could be either faulty design or lack of operator education. The FEI committee leading this study decided that "since the functional criteria in the design of a tractor demanded a specific configuration, education in the safe operation of the unit was the only solution." An educational farm program was developed but proved to be insufficient. Arndt (1971) further noted that, in 1951, the state of California required "canopies" to be installed on tractors used in the logging industry to prevent injury to the operator. Oregon also required canopies to be installed on tractors in the logging industry at about the same time. These states wanted to protect workers in the logging industry from falling objects, such as trees, rocks, and limbs. No overturn protection was required on these tractors. To test the protection afforded by the canopies installed on tractors, logs were dropped from controlled heights on top of the canopies, and then the tractors were rolled down a steep embankment. It was concluded that while overhead canopies were not intended for rollover protection, such canopies did offer some protection in rollover scenarios and reduced the likelihood of injury to operators during tractor rollovers.

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The authors are **Caleb M. Lindhorst,** Graduate Student, Department of Biological Systems Engineering, **Roger M. Hoy,** Professor, Department of Biological Systems Engineering, and Director, Nebraska Tractor Test Lab, **Santosh K. Pitla,** Assistant Professor, Department of Biological Systems Engineering, and **Michael F. Kocher,** Associate Professor, Department of Biological Systems Engineering, University of Nebraska, Lincoln, Nebraska. **Corresponding author:** Roger M. Hoy, 134 Splinter Labs, 35th & East Campus Loop, University of Nebraska, Lincoln, NE 68583; phone: 402-472-2442; e-mail: rhoy2@unl.edu.

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In 1954, a study was conducted in Sweden (Moberg, 1964) to examine the problem of agricultural and forestry tractor overturns and concluded that a protective frame or cab was needed. This study concluded that upset rollover tests were excessively destructive and, more importantly, unreproducible, which led to the development of the Swedish pendulum test. In this test, a tractor with a safety frame was anchored securely to the floor, and a mass of 2 metric tons was suspended from a cable, swung to the side a known distance, and then released to swing and strike the cab of the tractor. It was determined that variations in the velocity and mass of the pendulum block were not critical to the testing results as long as the total applied energy was the same. The amount of energy required was calculated from actual rollover tests and was supported by mathematical models that accounted for known variables in the design of ROPS (Klose, 1969). This test required one blow to the front and side as well as the application of a static downward vertical force. A study in 1967 (Watson, 1967) at Lincoln College in New Zealand concluded that the pendulum test was too severe for low-mass tractors and not severe enough for heavier tractors.

At the present time, the requirements for the dynamic test are described in ISO Standard 3463 (ISO, 2006a) and OECD Code 3 (OECD, 2017a). The static test requirements are described in ISO Standard 5700 (ISO, 2006b) and OECD Code 4 (OECD, 2017b). The ISO and OECD versions of these test standards are largely technically harmonized and, with regard to the scope of this technical note, are technically equivalent. The scope of ISO Standard 3463 and the field of application of OECD Code 3 currently limit application of the dynamic test to tractors with a reference mass of generally less than 6,000 kg. Larger modern agricultural tractors often have an unballasted mass in excess of 6,000 kg, so this study examined 47 wheeled tractors tested recently at the Nebraska Tractor Test Laboratory (Hoy et al., 2014, 2015, 2016). In this study, the highest tractor mass was 24,800 kg. Additionally, it is necessary to prove that ROPS are designed in a manner to provided adequate protection in cold weather conditions by demonstrating that the structural materials do not suffer cold weather embrittlement failures. In practice, this is accomplished according to the procedures found in ISO 5700 and OECD Code 4, which provide for the use of steels certified for resistance to cold weather embrittlement. However, with the advent of composite materials, it is now necessary to consider how to prove resistance to cold weather embrittlement for non-ferrous materials. A summary of the changes to the various ISO standards is shown below:

- 1989: ISO 3463 3rd edition published (ISO, 1989a).
- 1989: ISO 5700 3rd edition published; applicable to tractors with unballasted mass of not more than 15,000 kg and noted that further studies needed to be done on tractors with mass greater than 15,000 kg. The third edition was published to change the use of a seat reference point to a seat index point for establishing the operator clearance zone (ISO, 1989b).
- 1998: ISO 3463 3rd edition, Amendment 1 published to accommodate tractors with reversible seats (ISO, 1998a).
- 1998: ISO 5700 3rd edition, Amendment 1 published to accommodate tractors with reversible seats (ISO, 1998b).
- 2006: ISO 3463 4th edition published; an update of the 3rd edition, which was revised for harmonization with OECD Code 3 (ISO, 2006a).
- 2006: ISO 5700 4th edition published; eliminated upper mass limit (ISO, 2006b).

The scope of ISO 3463 restricts the tractor's maximum allowable ballasted mass to be "generally less than 6,000 kg," and it is therefore not applied when the tractor reference mass (a mass selected by the manufacturer that is not less than the unballasted mass) exceeds 6,000 kg. Further, few to no dynamic tests have been conducted in the last 20 years due to the overwhelming acceptance of the static testing procedures in ISO 5700 and OECD Code 4. Because new non-ferrous materials are now available for use in ROPS, it is necessary to modify the dynamic ROPS tests to allow tractors with reference mass greater than 6,000 kg to be tested so that a method of demonstrating resistance to cold weather embrittlement is available for all tractors.

OECD Code 3 outlines the process for dynamic testing of ROPS. In its current form, OECD Code 3 states that the ROPS supported on a tractor chassis must be struck by a block acting as a pendulum and be subjected to front and rear crushing tests. The specified mass of the pendulum block is 2,000 kg. The tires of the tractor are to fully support the mass of the tractor. Current restrictions from the scope of ISO 3463 and the field of application of OECD Code 3 are that the tractor mass must be greater than 600 kg but less than 6,000 kg. ISO 5700 and OECD Code 3 also require that the minimum width of the rear tires must be greater than 1,150 mm. OECD Code 7 (OECD, 2017c) is applicable to tractors narrower than 1,150 mm and with mass less than 3,500 kg. OECD Code 3 is performed while the tractor's tires support the tractor mass, which allows some of the energy from the pendulum drop to be absorbed by the tires. OECD Code 4, which outlines the process for static testing of ROPS, requires that the tractor axles be rigidly supported so that all of the applied energy is absorbed by the tractor frame, the ROPS, and the ROPS mountings. Tractors tested to Code 4 cannot be less than 600 kg, but there is no upper mass limit. Code 4 also requires that the minimum track width must be greater than 1,150 mm, and the mass ratio must not be greater than 1.75 (mass ratio = maximum permissible mass / reference mass, where maximum permissible mass is the maximum allowable mass of the tractor stated by the manufacturer, and reference mass is the mass selected by the manufacturer for calculation of energy inputs and crushing forces). OECD Code 3 and Code 4 have identical crushing tests, so the focus is restricted to the longitudinal and side tests.

Many tractors tested at the Nebraska Tractor Test Lab have an unballasted mass of more than 6,000 kg, which is the current upper limit for OECD Code 3 and ISO 3463. Therefore, the purpose of this study was to explore whether or not the existing dynamic test procedure is appropriate for tractors with a reference mass greater than 6,000 kg and, if not, propose appropriate modifications to the existing dynamic testing procedures. This study also explored the possibility of adapting some of the OECD Code 4 test procedures to the Code 3 testing procedure.

Review of Existing ROPS Codes and Standards

OECD Code 4 (OECD, 2017b) requires that the energy absorbed by the protective structure in longitudinal loading with no intrusion or exposure of the clearance zone must be equal to or greater than the required input energy based on the reference mass of the tractor:

$$E_{IL1} = 1.4M \tag{1}$$

where M is the reference mass of the tractor (kg), and E_{IL1} is the required energy for the first longitudinal load (J).

The reference mass is the mass selected by the manufacturer for the calculation of energy inputs and crushing forces to be used in tests. The reference mass must not be less than the unballasted mass and must be sufficient to ensure that the mass ratio does not exceed 1.75. The mass ratio is given by:

$$\text{Mass ratio} = \frac{\text{Maximum permissible mass}}{\text{Reference mass}} \tag{2}$$

where the maximum permissible mass is the maximum mass of the tractor stated by the manufacturer on the tractor's identification plate and/or operator's handbook.

OECD Code 4 requires that the energy absorbed by the protective structure in side loading must be equal to or greater than the required energy input:

$$E_{IS} = 1.75M \tag{3}$$

where E_{IS} is the required side loading energy (J).

OECD Code 3 and ISO 3463 use the following equations to determine the drop height of the center of gravity of the pendulum for the rear and side impact tests. For the rear impact test, the pendulum drop height is calculated by:

$$H = 2.165 \times 10^{-8} ML^2 \quad \text{or } H = 5.73 \times 10^{-2} I \tag{4}$$

where H is the pendulum drop height (mm), L is the wheelbase of the tractor (mm), and I is the moment of inertia about the rear axle (kg m^{-2}). The first equation is commonly used for calculating the drop height, as the moment of inertia about the rear axle is seldom known.

For impact on the side, the equation for pendulum drop height is:

$$H = 125 + 0.15M \tag{5}$$

ISO 3463 (2nd through 4th editions; ISO, 2006a) has a tractor mass range of 2,000 to 6,000 kg for this pendulum height equation; however, OECD Code 3 has a mass restriction of greater than 600 kg and generally less than 6,000 kg. The relationship between the energy absorbed by the protective structure and the pendulum drop height in ISO 3463 is described in subclause 7.2.3. This energy calculation is applicable to both longitudinal and side loading:

$$E = 19.6H \tag{6}$$

where E is the energy (J).

Objectives

With no further studies looking into equations for tractors with mass greater than 6,000 kg and the need to prove resistance to cold weather embrittlement, this study was conducted to meet the following objectives:

1. Can the dynamic test be extended to all tractors by simply removing the upper mass limit of 6,000 kg?
2. If simply removing the upper mass limit is impractical, can new energy equations for ROPS on tractors over 6,000 kg be developed that are appropriate?

Materials and Methods

Unballasted mass and wheelbase data for 47 wheeled tractor test reports published by the Nebraska Tractor Test Lab (Hoy et al., 2014, 2015, 2016) were used in this study (table 1). All wheeled and four-track tractors tested by the Nebraska Tractor Test Laboratory beginning in December 2014 with test number 2104 and ending with test number 2155 in 2016 were selected and included a wide range of tractor makes and models. Tractors equipped with two tracks were not included because these tractors do not have wheelbases. The energy values required by OECD Code 3, by ex-

Table 1. Tractors used in this study.

Test No.	Tractor Model	Mass (kg)	Wheelbase (mm)
2104	Massey Ferguson 7622	8482	2993
2105	John Deere 6195R	8494	2800
2106	John Deere 6215R	8573	2800
2107	John Deere 9370R	17955	3500
2108	John Deere 9420R	19568	3500
2109	John Deere 470R	20770	3500
2111	John Deere 520R	21491	3500
2113	John Deere 7310R	11226	2925
2114	John Deere 5075M	3749	2300
2115	John Deere 5085M	3758	2300
2116	John Deere 5100M	4171	2300
2117	John Deere 5115M	4216	2300
2118	CIH Magnum 180	9122	3005
2119	CIH Magnum 200	9945	3005
2120	CIH Magnum 220	9945	3005
2121	CIH Magnum 240	10197	3005
2122	New Holland T8.320	11046	3454
2123	CIH Magnum 280	12567	3055
2124	CIH Magnum 310	11437	3055
2125	New Holland T8.410	12603	3454
2126	CIH Magnum 380	14315	3155
2127	Cabela LM55H	2082	1935
2128	Cabela LM75	2581	2188
2130	John Deere 8345R	12619	3080
2131	John Deere 8370R	12528	3080
2133	John Deere 9570R	21870	3500
2135	John Deere 9620R	21804	4160
2136	John Deere 6175R	8466	2800
2137	John Deere 5055E	2701	2050
2138	John Deere 5065E	2708	2050
2139	John Deere 5075E	2708	2050
2140	John Deere 5075E	3218	2050
2141	John Deere 5085E	3683	2300
2142	John Deere 5100E	3685	2300
2143	John Deere 6105E	4790	2450
2144	John Deere 6120E	4826	2450
2145	John Deere 6135E	4928	2450
2146	John Deere 6145E	7026	2765
2147	John Deere 6155R	7033	2765
2148	CIH Magnum 310	16345	3155
2149	New Holland T8.410	16485	3550
2150	CIH Magnum 380	17418	3155
2151	Claas Xerion 4500	19651	3600
2152	Kubota M5-111	3565	2250
2153	Kubota M6-111	4538	2435
2154	Kubota M6-131	5125	2690
2155	Kubota M6-141	5125	2690

tending the current equation to tractors with mass greater than 6,000 kg, and by OECD Code 4 were plotted versus the given reference mass. For each tractor test report, the pendulum drop height and energy for the dynamic test were calculated for rear and side dynamic loadings using the unballasted mass as the reference mass. Energy was also calculated for both loadings used in the static ROPS test, and these energy values and drop heights were plotted.

Figure 1 compares the energy as a function of tractor reference (unballasted) mass for longitudinal loading (static test), and rear impact (dynamic test) calculated for the 47 tractor models used in this study. Because of the use of wheelbase squared or inertia terms in the calculation of the pendulum drop height for the rear longitudinal loading energy in the dynamic test, the energy values calculated for that test are not linear with respect to reference mass. The apparent outlier requiring 160,000 J is a tractor of similar mass and from the same manufacturer as the tractor represented by the data point immediately below, but it has a longer wheelbase. The energy applied in the dynamic test is determined by the pendulum mass and drop height. The pendulum mass is fixed at 2,000 kg, and the drop height is determined by equation 4. The energy applied in the static test is determined by measuring the force applied and the resulting deflection, with integration employed to determine the energy applied. The required energy is determined by equation 1. The dynamic energy requirements are higher than the static energy requirements due to the presence of tractor tires in the dynamic test and due to the different behavior of steel when high strain rates are present (Grimsmo et al., 2015). The energy values required for the static and dynamic loadings were similar for an unballasted tractor mass of up to about 4,000 kg. As tractor mass increased above 5,000 kg, the energy required for the dynamic rear impact rose at a higher rate than the energy required for the static longitudinal loading until, at an unballasted tractor mass of 20,000 kg, the energy required for the dynamic rear impact load was about 3.5 times the energy required for the static longitudinal loading.

A similar comparison is shown in figure 2 for the side impact test. As was true for the rear loading test, the energy required for the dynamic side impact loading test was greater than the energy for the static side loading test. The pendulum drop heights were calculated and plotted versus the reference

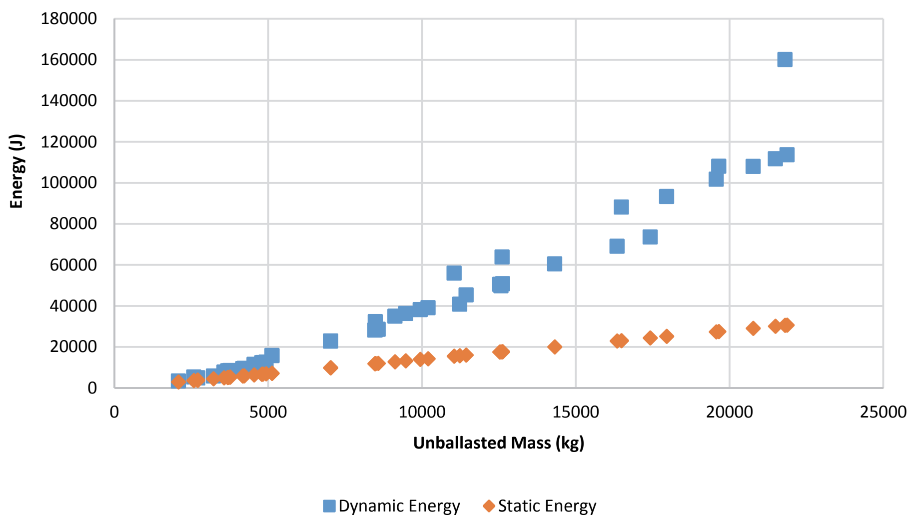

Figure 1. Longitudinal loading energy compared to reference mass for 47 tractors using equation 1 (OECD Code 4) for the static ROPS test and using equations 4 and 6 (OECD Code 3) to calculate the required pendulum drop height and energy, respectively, for the rear impact in the dynamic ROPS test.

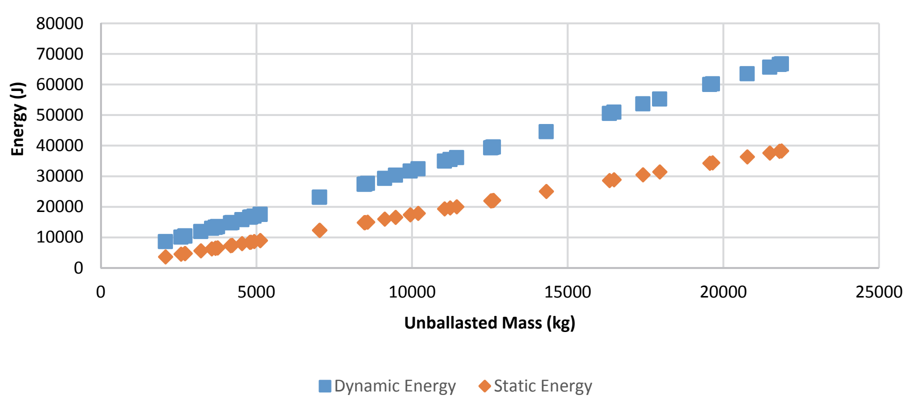

Figure 2. Side loading energy compared to reference mass for 47 tractors using equation 3 (OECD Code 4) for the static ROPS test and using equations 5 and 6 (OECD Code 3) to calculate the required pendulum drop height and energy, respectively, for the dynamic ROPS test.

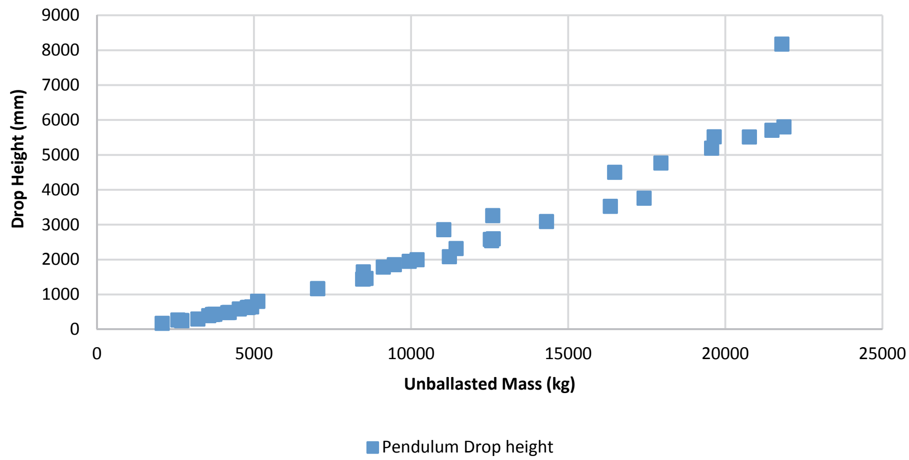

Figure 3. Pendulum drop height for longitudinal loading of 47 tractors using equation 4 in the OECD Code 3 dynamic ROPS test as a function of reference mass.

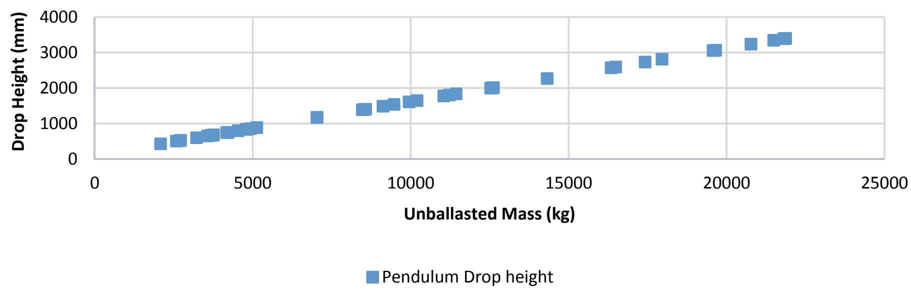

Figure 4. Pendulum drop height for side loading of 47 tractors using equation 5 as a function of reference mass in the OECD Code 3 dynamic ROPS test.

mass for the longitudinal rear impact test (fig. 3) and side loading test (fig. 4).

Results and Discussion

A comparison of the static and dynamic energy requirements in both the longitudinal and side loadings for the 47 tractor models used in this study reveals the excessive energy that the dynamic test imposes as tractor mass increases. The percentage differences by which the dynamic energy is greater than the static energy, relative to the static energy for the longitudinal and side loadings, are shown in figures 5 and 6, respectively.

In the longitudinal loading test, the percentage difference starts low at 10% and reaches 55% at 6,000 kg but then rises steadily to around 75% for tractors over 20,000 kg. In the side loading test, the percentage difference starts at 57% for low-mass tractors but declines to 43% for tractors over 20,000 kg.

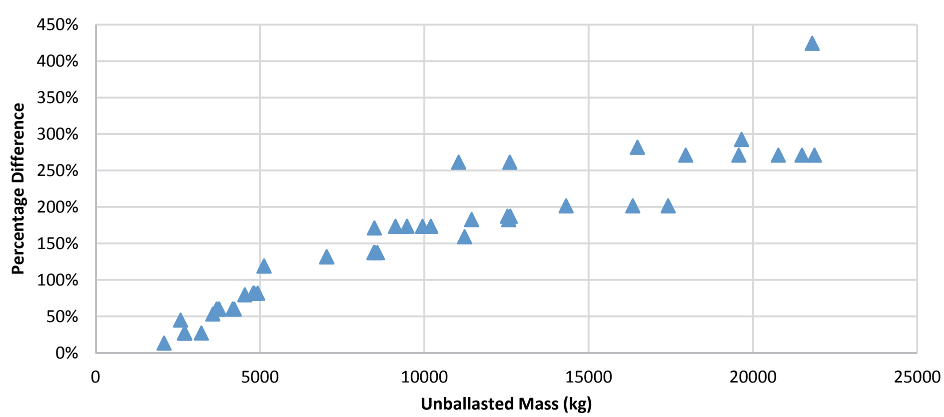

Figure 5. Percentage by which dynamic energy is greater than static energy, relative to the dynamic energy, in the longitudinal loadings of the OECD Code 3 (dynamic) and Code 4 (static) ROPS tests.

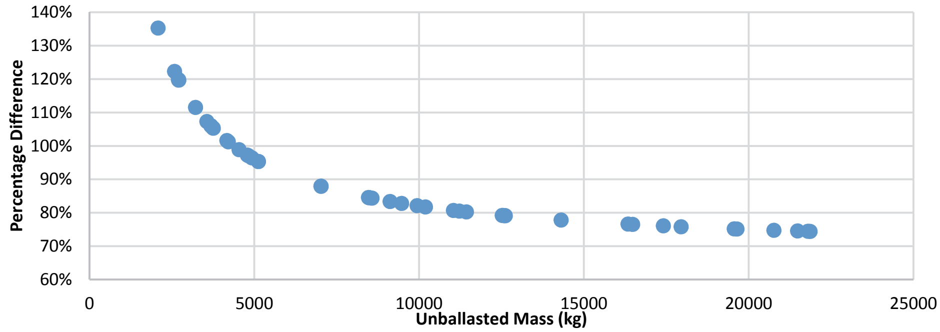

Figure 6. Percentage by which dynamic energy is greater than static energy, relative to the dynamic energy, in the side loadings of the OECD Code 3 (dynamic) and Code 4 (static) ROPS tests.

If the current equations are used for tractors over 6,000 kg, some pendulum heights for tractors would have to be more than 8.0 m for longitudinal loading and up to 3.5 m for side loading. When the height above ground at which the impact would have to be applied to the ROPS is considered along with the pendulum height, it becomes clear that the dynamic test would have to be conducted in a building that is more than 15 m tall to accommodate today's largest tractors. Because some tests must be conducted in a cold environment to prove cold weather embrittlement resistance, the structure size becomes expensive and impractical. Further, such drop heights are extreme and present a danger to the test engineers and bystanders conducting dynamic ROPS tests. Because the applied energy increases at a rate much greater than that found in the static test as the tractor mass increases beyond 6,000 kg, and the pendulum drop height required for such a test is unsafe, simply raising the upper mass limit of the existing dynamic test is clearly not reasonable.

As it is clear that simply extending the current dynamic energy equations by raising or removing the upper mass limit is not reasonable, it is appropriate to consider new energy equations. We must first consider how steel properties change when strain rates differ, as is the case when comparing static testing to dynamic testing.

Grimsmo et al. (2015) examined the effects of strain rates on structural steel joints from quasi-static to high rates of strain typically experienced during explosions and concluded that load velocity has an effect on strain rate. Watson (1967) noted that increasing strain rates resulted in higher yield strengths in the typical mild steels used then and now in ROPS structures. Watson's analysis of ROPS structures noted that dynamic energy needed to be 9% higher than static energy during sideways overturning on soft ground and 45% higher for side overturns on hard surfaces, such as concrete, to achieve results comparable to static testing. Watson also concluded that the tractor tires absorb 10% of the energy in a normal side overturn, with the ROPS structure absorbing the remaining 90%. Watson assumed that the tractor chassis remained rigid and that all permanent deformation occurred in the ROPS structure and components.

Continuing with this assumption in the present study, if we accept that the existing static test procedure is adequate, we can therefore propose new sets of dynamic energy equations based on the static equations, with their validity verified by checking that the resulting permanent deflections of the ROPS structures are the same whether they are achieved in the static test or the dynamic test.

Consider first a dynamic test in which the tractor chassis is rigidly restrained without tires in the same manner as the static test. Assuming that the tractor frame and mountings are rigid with respect to the ROPS and that the pendulum can be considered frictionless, the energy level of the longitudinal loading may be increased by 45% above the static test, which yields a new equation for the extended dynamic test:

$$E_L = 2.03M \tag{7}$$

In a similar manner, the side impact energy from equation 3 when increased by 45% becomes:

$$E_S = 2.54M \tag{8}$$

Secondly, we can consider restraining the tractor chassis with the chassis supported on the tractor tires in the same method presently used in the dynamic test. Watson (1967) determined that 10% of the dynamic applied energy is absorbed by the tires. Franceschetti et al. (2014) noted that perhaps as much as 50% of the dynamic applied energy is absorbed by the tires. Grimsmo et al. (2015) established that additional dynamic energy is required to achieve the same deflections as a static test, but it is not clear what portion of the additional energy predicted by Franceschetti et al. (2014) is absorbed by the tires and what portion is due to the different behavior of steel when loading is present at such high strain rates.

Because, in the case of a tractor rigidly restrained and subjected to a dynamic test, an increase of 45% in the static energy was predicted to result in similar deflection with respect to the existing static test, it is appropriate to increase the dynamic energy required by the additional 10% established by Watson (1967) rather that the 50% reported by Franceschetti et al. (2014), which includes the combined effect of higher strain rates and energy absorbed by the tires:

$$E_L = 2.23M \tag{9}$$

In a similar manner, the side impact energy from equation 8 when increased by 10% becomes:

$$E_S = 2.79M \tag{10}$$

Figure 7 shows the proposed required dynamic energy for longitudinal loading of a rigidly supported tractor frame (eq. 7) and a tractor secured on its tires (eq. 9). The energy required by the existing Code 3 equation is shown for comparison. Figure 8 shows the corresponding dynamic energy values for the side loading of a rigidly supported tractor frame and a tractor secured on tires.

The required drop height for the 2,000 kg mass can be easily found in terms of the tractor's reference mass using the potential energy equation:

$$E = mgh \tag{11}$$

where m is the mass of pendulum (kg), g is the gravitational constant (9.8 m s^{-2}), and h is the required pendulum height (m).

The resulting drop heights of the pendulum using equations 7 through 10 can therefore be found as follows:

Using equation 7: $H = 0.104M$ (12)

Using equation 8: $H = 0.130M$ (13)

Using equation 9: $H = 0.114M$ (14)

Using equation 10: $H = 0.142M$ (15)

Figure 9 shows the calculated drop heights for a tractor rigidly supported (eq. 12) compared with a tractor supported on tires (eq. 14). The calculated drop height using the existing Code 3 equation is also shown for comparison purposes. Figure 10 shows similar information for side loading drop height calculations for a tractor rigidly supported (eq. 13) and a tractor supported on tires (eq. 15).

Before continuing, it is worthwhile to consider the practicality of the results of equations 7 through 10 and equations 12 through 15. For tractors with an unballasted mass of less than 6,000 kg, the maximum predicted drop height does not exceed 1,000 mm. Considering that the potential energy of the pendulum raised to its initial drop height is converted to kinetic energy upon impact with the ROPS, it is clear that

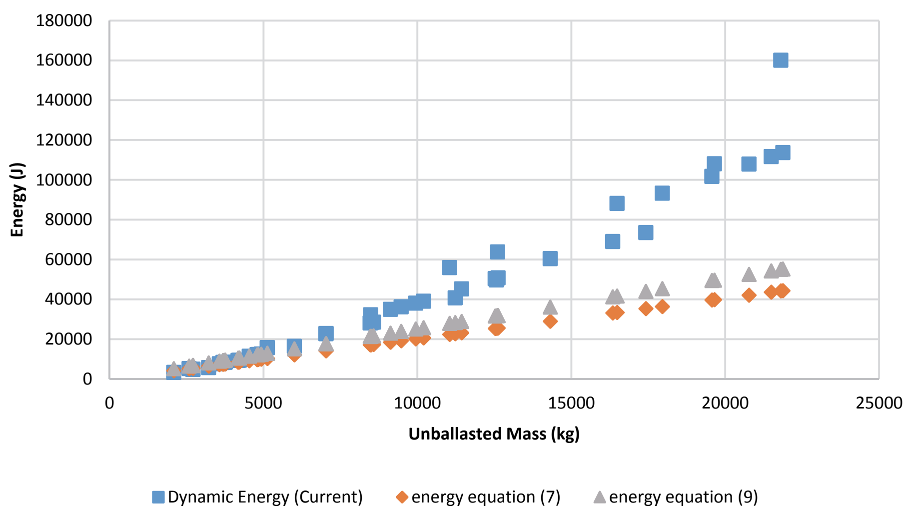

Figure 7. Comparison of rear longitudinal dynamic energy loading requirements for a tractor rigidly supported (eq. 7), a tractor supported on tires (eq. 9), and the current OECD Code 3 ROPS test equation extended beyond 6,000 kg unballasted tractor mass.

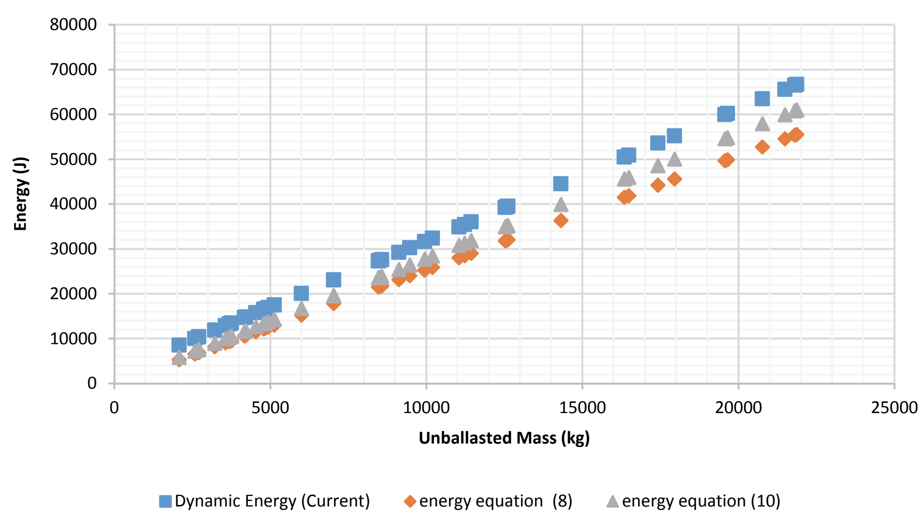

Figure 8. Comparison of side dynamic energy loading requirements for a tractor rigidly supported (eq. 8), a tractor supported on tires (eq. 10), and the current OECD Code 3 ROPS test equation extended beyond 6,000 kg unballasted tractor mass.

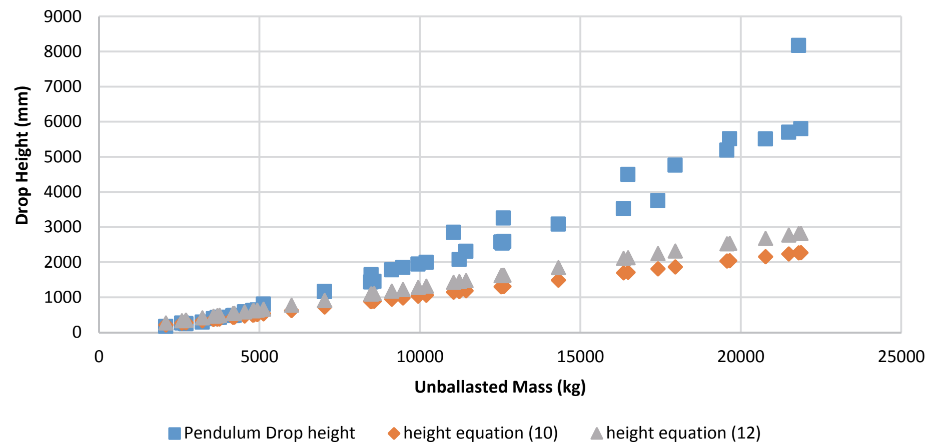

Figure 9. Comparison of rear longitudinal pendulum drop heights for a tractor rigidly supported (eq. 12), a tractor supported on tires (eq. 14), and the pendulum drop height using the current OECD Code 3 ROPS test equation extended beyond 6,000 kg unballasted tractor mass.

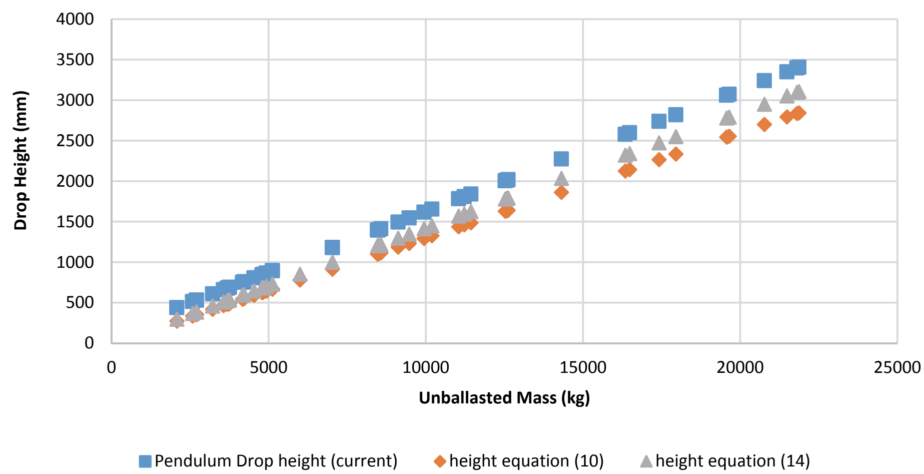

Figure 10. Comparison of side pendulum prop heights for a tractor rigidly supported (eq. 13), a tractor supported on tires (eq. 15), and the pendulum drop height using the current OECD Code 3 ROPS test equation extended beyond 6,000 kg unballasted tractor mass.

the impact velocity of the pendulum on the ROPS is proportional to the square root of 2*g* times the pendulum drop height. For example, a drop height of 2,000 mm results in an impact velocity 1.414 times higher than a drop height of 1,000 mm. As indicated by Grimsmo et al. (2015) and Watson (1967), maintaining the strain rate of the impact is critical to achieving comparable test results when compared to the static test. Therefore, it is necessary to consider adjusting the potential energy of the pendulum by adjusting the pendulum mass so that the maximum drop height and corresponding impact velocities remain similar to those that are currently used in the dynamic test. Due to the wide variety of tire sizes and configurations available for each tractor model, only a rigidly supported tractor should be considered.

Figure 11 shows the proposed rear longitudinal impact energy required for a rigidly supported tractor in a dynamic ROPS test using equation 7. Figure 12 shows the pendulum drop heights calculated for a series of pendulum masses proposed for use with tractors of various mass ranges. As shown in figure 12, no drop height exceeds 1,000 mm. For tractors of less than 7,000 kg unballasted mass, equation 7 was applied using a traditional 2,000 kg pendulum. Using equation 11 with the proposed pendulum masses of 4,000 and 6,000 kg gives the following equations for pendulum drop height.

For tractors with unballasted mass of 7,000 kg or more and less than 14,000 kg, a pendulum mass of 4,000 kg was used, and the resulting equation for drop height is:

$$H = 0.0518M \tag{16}$$

For tractors with unballasted mass of 14,000 kg or more and less than 23,000 kg, a pendulum mass of 6,000 kg was used, and the resulting equation for drop height is:

$$H = 0.0345M \tag{17}$$

In a similar manner, figure 13 shows the side loading energy requirements for dynamic testing of a ROPS on a rigidly supported tractor. Figure 14 shows the drop height requirements for the side loading using the same three pendulum sizes as presented for longitudinal loading. For tractors of less than 7,000 kg unballasted mass, equation 8 was applied using a traditional 2,000 kg pendulum. For tractors with unballasted mass of 7,000 kg or more and less than 14,000 kg, a pendulum mass of 4,000 kg was used, and the resulting equation for drop height is:

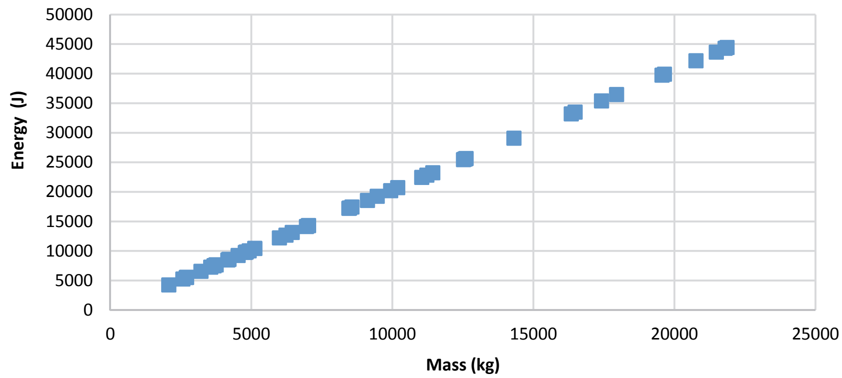

Figure 11. Proposed rear longitudinal impact energy requirements (eq. 7) for dynamic testing of a ROPS on a rigidly supported tractor.

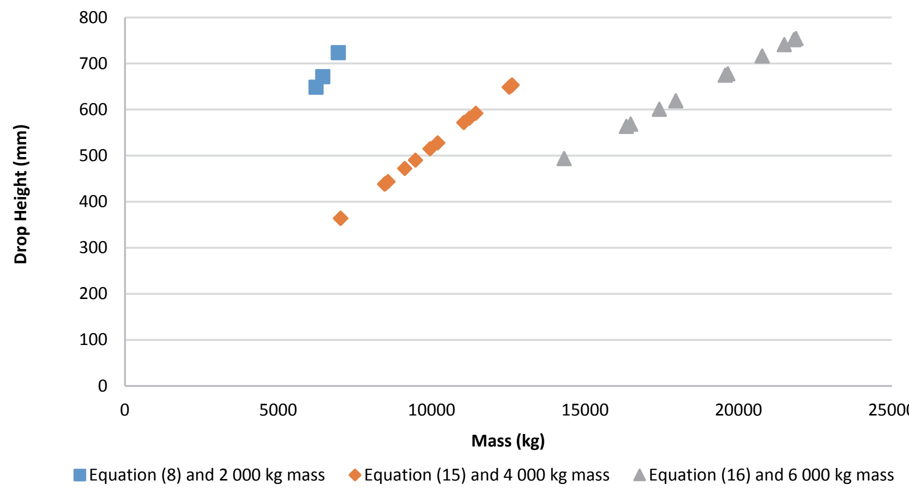

Figure 12. Proposed drop height requirements of three different pendulum masses for applying rear longitudinal impact energy (eq. 7) in dynamic testing of a ROPS on a rigidly supported tractor.

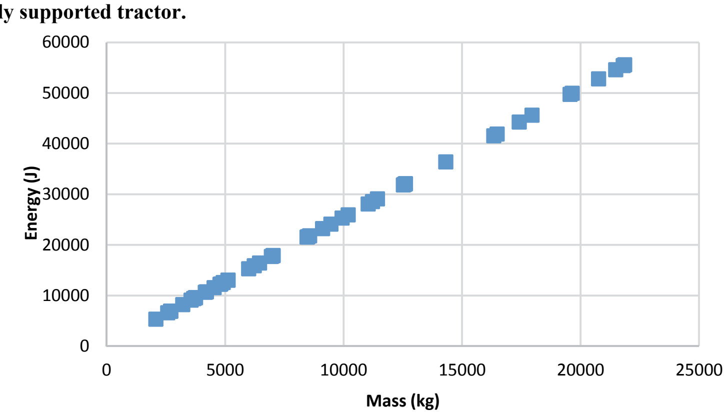

Figure 13. Proposed side impact energy requirements (eq. 8) for dynamic testing of a ROPS on a rigidly supported tractor.

$$H = 0.0647M \quad (18)$$

For tractors with unballasted mass of 14,000 kg or more and less than 23,000 kg, a pendulum mass of 6,000 kg was used, and the resulting equation for drop height is:

$$H = 0.0432M \quad (19)$$

Conclusions

The existing energy and pendulum drop height equations from OECD Code 3 and ISO 3463 were examined to determine whether or not the application of OECD Code 3 could be extended to tractors with unballasted masses greater than 6,000 kg. Extending the existing equations was found to be neither practical nor correct. New equations for applied energy and pendulum drop heights were developed, which resulted in three different pendulum masses selected so that the

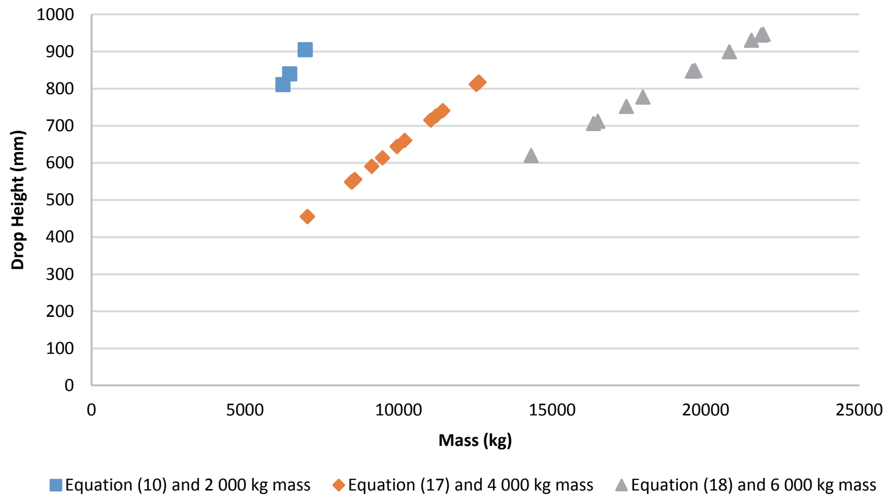

Figure 14. Proposed drop height requirements of three different pendulum masses for applying side impact energy (eq. 8) in dynamic testing of a ROPS on a rigidly supported tractor.

drop height would remain less than 1,000 mm, thereby keeping the strain rate within the range of experience with the current static testing procedure. It was further concluded that because of the much greater variety of tire sizes and mountings, only rigidly supported tractors should be used for dynamic testing.

These energy and pendulum drop height equations are intended to provide an impact test that will achieve the same results as the existing static ROPS test found in OECD Code 4 for higher-mass tractors; however, testing of these equations has not been undertaken, and such confirmation testing is necessary to verify the proposal presented in this technical note. It is conceivable that as tractors become heavier, an additional pendulum mass of 8,000 kg could be employed; however, as no such heavier tractors exist at this time, there is limited opportunity for qualification of an additional higher-mass pendulum. At this time, it is recommended that the 6,000 kg pendulum be limited to tractors with reference masses of less than 23,000 kg so that the drop height remains less than 1,000 mm.

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